Renewable and Sustainable Energy Reviews 24 (2013) 187–197

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Analyses of the decarbonizing Thailand's energy system toward low-carbon futures

Aumnad Phdungsilp*, Teeradej Wuttipornpun

Department of Industrial Engineering, Faculty of Engineering, King Mongkut's University of Technology North Bangkok, Bangkok, Thailand

ARTICLE INFO

Article history:
Received 28 August 2012
Received in revised form
4 March 2013
Accepted 15 March 2013
Available online 15 April 2013

Keywords:
Carbon emissions
Decarbonization
Energy scenarios
Low-carbon energy systems

ABSTRACT

Thailand is heavily dependent on imported fossil fuels. The utilization of energy resources is the main source of CO_2 emissions. Thus, restructuring current energy system is essential for the realization of low-carbon futures. Efficient and rational implementations of low emission reduction strategies and policies require application of energy system models that have the ability to estimate the baseline energy demand and CO_2 emissions, and to explore technical and economic effects of different strategies over time. This paper reviews and discusses the perspective of low-carbon energy systems in the case of Thailand. It analyzes the projected development of energy system in Thailand. The literature on modeling of energy systems is analyzed and discussed. The paper presents a quantitative comparison of the selected energy model applications in terms of energy demand and energy-related CO_2 emissions. The paper explores the potential pathways using findings from existing modeling studies to guide the development of a low-carbon energy system within a backcasting framework. It is found that there are wide ranges of projected emissions paths across the models. The findings suggest that there is sufficient technical potential to achieve a low-carbon target by 2030.

Contents

1. Introduction

The most rapid growth in energy demand is projected for nations outside the Organization for Economic Cooperation and Development (non-OECD countries). Total energy consumption in non-OECD nations was increased by 73% compared to a 15% increase in OECD nations [1]. The primary energy demand in non-OECD Asia is expected to be 5285 Mtoe in 2020 and 7240 Mtoe in 2035 [2]. Thailand is one of the fast growing economy and energy demand in non-OECD Asia countries. Thailand's energy sector emits significant amount of CO_2 emissions, thus ranking the 20th in the world [3]. Despite the importance of climate change mitigation, however, Thailand is currently no clearly defined the nation's emission reduction targets. Keeping in view of the rising emissions, it is imperative that Thailand starts to avoid embarking

* Corresponding author. Tel.: +66 255 520 00.
E-mail address: aumnad@gmail.com (A. Phdungsilp).

1364-0321/$ - see front matter
http://dx.doi.org/10.1016/j.rser.2013.03.050

on a high-carbon growth path and instead takes a low-carbon pathway. Delaying action would lock the country into high-carbon infrastructures and would require more costly retrofitting of energy capital stocks such as power plants, buildings and transport networks in the future.

The decarbonization of energy systems can be measured by numerical index of the ratio of CO_2 emissions to total primary energy consumption. Another indicator is the carbon intensity of economic output, expressed as the ratio of CO_2 emissions to gross domestic product (GDP) [4–6]. Carbon intensity of economic output is a common measure in the analysis of changes in CO_2 emissions. The Japanese scholar Kaya [7] proposed Kaya formula that expresses total CO_2 emissions as the product of (1) carbon intensity of energy supply (2) energy intensity of economic activity, (3) economic output per capita, and (4) population scale. Following key variables in the Kaya formula can help to determine low-carbon growth pathways. The Kaya formula provides an intuitive approach to the interpretation of historical trends and future projections of CO_2 emissions. This interpretation has been termed a low-carbon society (LCS). Furthermore, the vision of LCS is also described as low-carbon economy, energy decarbonization, and carbonless economy [4,8–10]. Usually, transitions toward a low-carbon pathway are not in line with current trends, and will require drastic emission reductions. Such transition can be defined as economic growth with low-carbon intensity or clean energy development. Nakata et al. [4] clearly described the energy transition pathways and LCS in both developed and developing countries. They suggested that greater efforts are needed to realize the LCS to minimize the impact of climate change. These efforts are a combination of policies and measures across multiple sectors and activities of the economy. Moreover, recent research in transitions studies argues that transitions will require some combination of technological, economic, political, institutional, and socio-cultural changes [11].

The transition pathways to low-carbon futures in developing countries such as Thailand would be different from developed countries. This paper reviews and discusses the perspectives of low-carbon energy systems in the case of Thailand. The first purpose of this paper is to review energy scenarios and evaluate energy models that have been applied to energy scenario studies in Thailand. The existing literature on energy systems modeling and applications in Thailand is analyzed. The paper presents a current situation of energy consumption and energy-related CO_2 emission trends from Thailand's energy sector. The paper provides a quantitative comparison of the selected energy model applications in terms of energy demand and CO_2 emissions. The second purpose is to explore the potential pathways to a low-carbon energy system using findings from existing energy studies within a backcasting framework. This part depicts future technology and policy roadmap toward a low-carbon energy system. This study can provide opportunities for Thailand to decide on the development of low-carbon energy futures.

2. Current snapshot of energy situation and emission trends in Thailand

Thai energy sector faces challenges with limited resources availability, environmental impact and climate change like other imported energy countries. Thailand is highly dependent on fossil fuels together with the growing concern about the impacts of climate change have led many governments and organizations to reduce the emissions from energy sector. Achieving a low-carbon energy system requires an understanding of the current situation and prospective futures. This section discusses the energy situation and energy-related CO_2 emission trends in Thailand. It also makes an attempt to compare Thailand's emission trends with other countries in Southeast Asia.

A snapshot of energy situation in Thailand can be presented with five main components, including total primary energy supply, domestic primary energy production, imported energy, exported energy, and final energy consumption. Total primary energy supply in 2011 was 124,086 ktoe. These were comprised of commercial energy (81.6%), renewable energy (17.4%), biofuel (0.8%), and others (0.2%). The main sources of domestic primary energy included crude oil, condensate, natural gas, lignite, and renewable energy sources. Domestic primary energy production, imported energy and exported energy were 74,126 ktoe, 64,472 ktoe and 11,053 ktoe, respectively. The final energy consumption was 70,562 ktoe, which increased 0.4% from the previous year. Petroleum products accounted for 46.9% of the total final energy consumption, followed by electricity, traditional renewable energy, coal and its products, commercial renewable energy, and natural gas shared 18.0%, 13.1%, 9.3%, 6.4%, and 6.3%, respectively [12]. This means that fossil fuels are dominated the energy system in Thailand. Fig. 1 shows the share of final energy consumption by economic sectors in 2011.

Due to rapid economic growth over the past decades, the industrial sector contributes the largest share of total final energy consumption and follows closely by transport sector. Thailand's industrial sector consists of manufacturing, construction and mining industries. The manufacturing industry is significantly consumed more energy than the mining and construction industries, accounting for about 98.5% of total industrial energy consumption. The industrial sector is expected to increase its energy consumption to 81,189 ktoe in 2030, and will maintain the largest share for 49.3% of total final energy demand [13]. Highly energy-intensive industries, such as food and beverage, non-metallic and chemical, make up over 70% of total industrial energy demand. The transport sector is also expected to grow faster due to rapid urbanization and the rise of the consumer income. High energy demand in transport sector results from urban form, lack of fuel economy standard, and short public transit network, which increases the use of personal vehicles. Road transport dominates the transport mode and contributes the largest share of transport energy demand. The building sector (residential and commercial) accounts for approximately 23% of total energy consumption. This sector consumes mainly electricity to provide energy services. Air-conditioning accounts for more than 50% of energy consumed in a building. Building sector expects to grow significantly due to increasing floor spaces in commercial buildings [12,13].

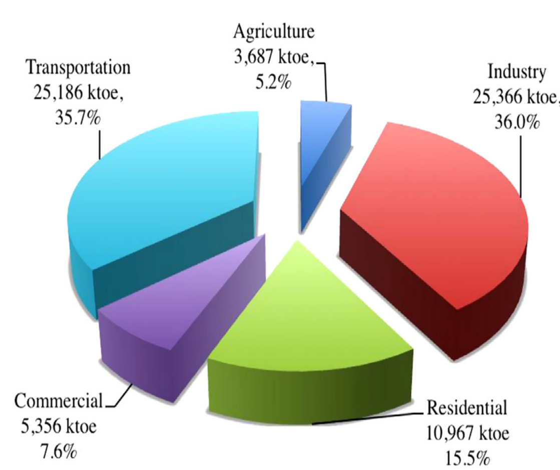

Fig. 1. Share of final energy consumption by economic sectors in 2011.
Source: DEDE [12].

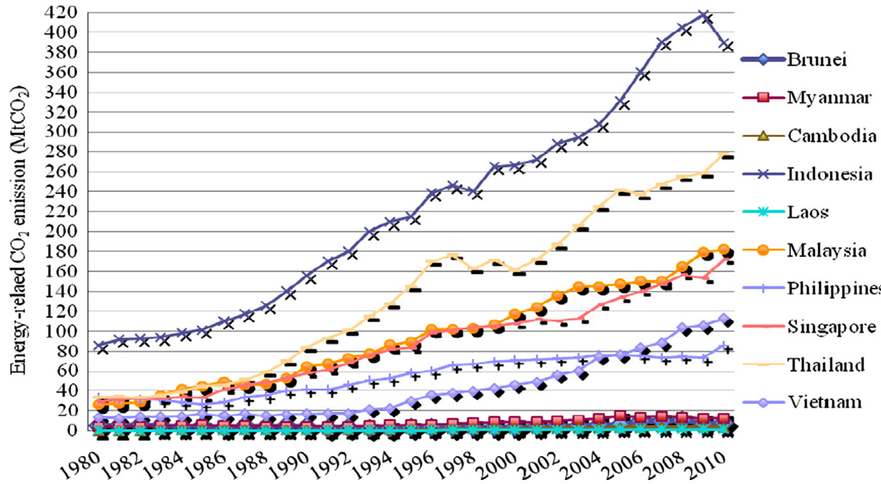

Fig. 2. Trends of energy-related CO_2 emissions in ASEAN member states.
Source: U.S. Energy Information Administration [3].

Total energy demand in Thailand is expected to grow more than double over the next two decades. The energy sector is the largest source of CO_2 emissions. Thailand's energy and carbon intensity is several times higher than leading developed countries [14]. During 1980–2010, Thailand's energy-related CO_2 emissions increased by 24.3% from 33.56 $MtCO_2$ in 1980 to 278.49 $MtCO_2$ in 2010 with an annual average growth rate of 7.57%. Comparing with other ASEAN (Association of Southeast Asian Nations) member states during the same period, Indonesia emitted the largest emissions and followed by Thailand, Malaysia, Singapore, Vietnam, the Philippines, Myanmar, Brunei, and Cambodia [3]. Fig. 2 presents a comparison of CO_2 emissions from energy consumption in ten ASEAN countries. In terms of CO_2 emissions per capita, it was found that Singapore emitted 36.63 $MtCO_2$ per capita in 2010, ranked the first in ASEAN, and followed by Brunei, Malaysia, Thailand, Indonesia, Vietnam, the Philippines, Cambodia, Myanmar, and Laos. Thailand emitted 4.15 $MtCO_2$ per capita with an increase of 16% from 1980 [3]. The key challenge for Thailand is to avoid a high-carbon growth path. To address this challenge, in the short term Thailand will need to accelerate energy efficiency improvements in the building, industry, power, and transport sectors, and to manage the growth in energy service demand. In the medium to long term, the emission reductions will come from low-carbon technologies for power generation, including renewable energy and carbon capture and storage.

3. Energy systems modeling and application in Thailand

Energy models are increasingly used to provide insights into how energy systems can evolve in the future. Analyzing possible pathway to a low-carbon energy system and its implication is a complex task, and this can be addressed through the application of energy models. These models represent the interactions of multiple components of the energy system based on mathematical formulations. In general, energy models can be classified based on analytical approach (top-down and bottom-up), purpose of the analysis (forecasting, exploring and backcasting), methodology (economic equilibrium, econometrics, optimization, and simulation), mathematical approach (linear programming, mixed integer programming and dynamic programming), geographical coverage (global, regional, national, and local), time horizon (short, medium and long term), and data requirements (qualitative and quantitative) [4]. Several modeling approaches have been used to analyze the future trends of energy demand and greenhouse gas (GHG) emissions, and to develop low emission reduction strategies. Energy models have been used to answer different types of questions concerning how economy, technology and environment interact. They are constructed and applied based on assumptions about socio-economic development, availability of technologies and the rate of technological progress. A variety of energy scenario studies and energy modeling tools have been used to envision how GHG emission reductions can be made using commercial or near commercial low-carbon and advanced technologies and fuels [15–19]. These studies show that the transport and power sectors must be significantly decarbonized if deep economy-wide emission reduction targets are to be achieved. This section presents the notion of energy models, energy scenarios and their applications to analyze a low-carbon energy system in Thailand.

3.1. Organizing the low-carbon energy scenarios literature

The approach to arranging literature on low-carbon energy scenarios in this paper follows the previous methodological approach based on typology proposed by Hughes and Strachan [20] with a particular focus on the case of Thailand. Accordingly, the typology has the following three categories:

- Trend-based studies: Scenarios developed around different combinations of broad and high level extrapolated trends.
- Technical feasibility studies: Scenario based around demonstrating the technical feasibility of the energy systems to meet energy demand and other constraints.
- Modeling studies: Complex quantitative models are used to generate results (scenarios). In most cases, the models work within an end-point carbon constraint.

The three approaches have different characteristics. Each type has different individual strengths and weaknesses. Trend-based studies allow for more detail speculation in areas of future social and cultural experience. It aims to provide vivid images of how people would live and interact with each other and with technologies in various futures. Technical feasibility studies allow a highly controlled theoretical manipulation of physical energy systems. Modeling studies combine technological details with data on resource availability and trade-offs and wider economic issues. In some cases the modeling approaches serve similar purpose to the technical feasibility studies. Both methods are able to provide depictions of energy system supply mixes that will meet energy services. However, modeling studies are able to employ greater

Table 1
List of reviewed papers on energy systems modeling in Thailand.

Category and exercise	Source	Scope of study
Trend driven studies		
Thailand long-term load forecasts	NIDA [21]	Electricity system
Energy forecasting for provincial energy planning	Charusiri and Ubolwat [22]	City level and energy demand
Transport energy demand	Limanond et al. [23]	Transport sector
Technical feasibility studies		
Assessment of energy saving potential in residential sector	Limmeechokchai and Chaosuangaroen [24]	Energy demand from residential sector
Assessment of cleaner electricity generation technologies	Limmeechokchai and Suksuntornsiri [25]	Electricity system
Effects of carbon tax on GHG mitigation	Shrestha et al. [26]	Energy system
Technology alternatives for energy demand reduction and GHG mitigation	Pongthanaisawan and Sorapipatana [27]	Road transport sector
Energy demand and supply under electricity generation scenarios	Pinthong and Wongsapai [28]	Electricity system
Energy resource development and energy security under CO_2 emission constraint	Watcharejyothin and Shrestha [29]	Energy system
Renewable energy demand and supply	Eakpaopan et al. [30]	Renewable energy supply
Impacts of alternative energy-environmental scenarios	Chaivongvilan and Sharma [31]	Energy system
Energy and carbon modeling	Phdungsilp and Wuttipornpun [32]	Industrial sector
Study of ethanol as a diesel substitute in Thailand	Chollacoop et al. [33]	Road transport energy demand
Modeling studies		
Sustainable energy development strategies	Tanatvanit and Limmeechokchai [34]	Energy demand in residential, industrial and transport sectors
Scenario-based analyses of energy system development	Shrestha et al. [35]	Energy system
Power sector scenarios	Mulugetta et al. [36]	Electricity system
Economics of climate change	ADB [37]	Energy sector in Thailand and other four countries
Integrated energy and carbon modeling	Phdungsilp [38]	Energy demand and renewable energy supply at city level
Spatial energy system modeling	Suwanapal [39]	Energy system and bioenergy
Outlook of long-term energy-related GHG	Wangjiraniran [40]	Energy system
Impact of economic restructuring on the energy system	Wangjiraniran et al. [41]	Energy system
Thailand's low-carbon scenario 2030	Winyuchakrit et al. [13]	Energy system

level of technological details and some models are able to express wider economic issues [20]. Allocating literature review into the three categories provides a useful mechanism for discussion of low-carbon energy scenarios in a systematic way.

Literature surveys were collected from three main sources of publication from 1990 to 2011. It revealed that energy studies within the scope of this study found from 2003 to 2011. Source one is scientific journals focusing on energy issues such as Energy Policy, Energy, Applied Energy, and Renewable and Sustainable Energy Reviews. Source two is journals covering the broad areas of environment e.g., Climate Policy, Environmental Modeling and Assessment, Ecological Economics, and Journal of Industrial Ecology. Source three is non-journal publications, including conference proceedings, book chapters, reports, theses, and websites. It should be noted that the review is focused on the energy studies in Thailand only. Table 1 lists the selected studies for review in this paper. It is found that many studies focus on technical energy system aspects. Some studies deal with economics of the energy systems and give attention to the social aspect. Dominant methodologies of energy scenario studies in Thailand have been the technical feasibility studies and modeling studies. The literature in general lacks the studies that make effort to integrate both societal and techno-economic issues. Scenarios across the three categories have given a minor consideration of political dynamics. Policy options often treated as external assumption rather than integral into the scenario.

3.2. Model assessment and characteristic

There are some studies focused on energy and carbon emissions in Thailand. These studies are estimated future energy demand and energy-related CO_2 emissions under different scenarios on national or sectoral basis. Understanding the energy and emission pathways is a fundamental to the transition toward LCS. Using the knowledge gained through the previous section, selected energy modeling tools were reviewed to assess for comparative analysis, and to identify the characteristics of energy models.

Table 2
Evaluation matrix to select energy models.

Criteria	AIM	ENPEP-BALANCE	LEAP	MARKAL	MAED-MESSAGE
Users	2	3	5	3	2
Applications	5	3	5	5	3
Data requirements	4	4	3	4	4
Outputs	4	3	5	5	4
Ease of use	1	2	3	1	2
Average	3.2	3.0	4.2	3.6	3.0

Energy models are developed using theoretical and analytical methods of several disciplines, including engineering, econometrics, operations research, and computer sciences. This paper limits a survey to renowned energy models in the literature and models that have been applied for Thailand. These models vary widely in their approaches, methodologies, data requirements, and outputs. Therefore, the evaluation procedures are consisted of two stages. In the first stage, the criteria for inclusion of models in the evaluation are following:

- Widely apply in Thailand by Thai researchers;
- Widely accept in a variety of international research institutes;
- Generally to be credible;
- Actively being developed and professionally supported; and
- Primarily design for integrated energy and GHG analysis.

Initially, the survey was identified 15 energy models that have been applied for energy and climate change mitigation studies in Thailand. Based on the above criteria, six models were included

in the second stage for final analysis. These are Asia-Pacific Integrated Model (AIM), Energy and Power Evaluation Program (ENPEP-BALANCE), Long-range Energy Alternatives Planning (LEAP) system, MARKet Allocation Model (MARKAL), and Model for Analysis of Energy Demand and Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MAED-MESSAGE). The criteria for evaluation in the second stage are:

- Users—who and how many people (mainly Thai researchers) has been used the model and technical assistance from model developers;
- Applications—what applications can the model be used for;
- Data input requirements—basic characteristic about the types of input data;
- Data outputs—e.g., energy consumption, CO_2 emissions, cost, and other pollutants; and
- Ease of use–structure and complexity of model, level of effort required and cost of re-run the model.

The goal of the review is to assess and compare energy models that have been applied to energy analysis in Thailand. It should be noted that the assessment criteria in this review are followed the guideline in Training Handbook on Mitigation Assessment for Non-Annex Parties [42]. The assessment was performed in a workshop of invited experts under the project of Research Policy in the Context of Sustainable Development and Low Carbon Economy [43]. The assessment processes started from evaluation of each model with respect to the criteria. The value scale was constructed simply by direct judgment. The criteria were scored in a group of experts by applying five-point scale, giving five points to the maximum and one point to the minimum attribute value (score 1= very low, 2= low, 3=medium, 4= high, and 5= very high). Participants were discussed until a consensus could be reached. Then, the qualitative information translated into a quantitative value scale. Results of the evaluation against the criteria in terms of users, applications, data requirements, prospective outputs, and ease of use are presented in Table 2. In addition, Table 3 presents a detail comparison of features of the energy models included in the final analysis. The six models selected for the comparison all share the same bottom-up type. The accounting framework appears to be more popular because of its flexibility and not required high skill levels for the users.

Energy models have been applied based on different analytical approaches and methodologies. Typically, these applications focus on the feasibility of changes in multiple aspects of the energy systems such as the potential of renewable energy utilization, the penetration rate of high efficiency devices, the analysis of impacts on a specific demand sector (i.e., transport, industry and building), and the inclusion of aspects beyond energy and environment interactions. They can be applied to aid decision-making in energy planning, to analyze energy policies and implications arising from the introduction of technologies. From the evaluation, it was found that most of the standard modeling tools are suitable for low-carbon energy system studies. The bottom-up accounting type model, such as LEAP, is widely used in Thailand because of its flexible data requirements and not high skill needs for the users. Also, the accounting model can include the environmental effects related to energy production, conversion and use by incorporating appropriate environmental factors. However, this model type does not look for an optimal solution. The inability to analyze

Table 3
Comparison of tools inclusion in the final analysis.

	AIM	ENPEP-BALANCE	LEAP	MARKAL	MAED-MESSAGE	
Type	Top-down and bottom-up	Bottom-up	Bottom-up	Bottom-up	Bottom-up	Bottom-up
Scope	Large-scale climate policy assessment	Integrated energy and GHG scenarios	-Energy system analysis -Integrated energy and GHG scenarios	Integrated energy and GHG scenarios	Demand forecasting	Supply side
Approach	Equilibrium	Equilibrium	Accounting	Optimization	Accounting	Optimization
Geographical coverage	Regional/country	Flexible	Flexible	National/state/regional	Flexible	Flexible
Activity coverage	Demand and supply	Demand and supply	Demand and supply	Demand and supply	Demand	Supply
Level of	disaggregation	Industry, transport, household and service	Industry, transport, household and service	Industry, transport, household and service	Industry, transport, household and service	Industry, transport, household and service
-						
Strengths	Using bottom-up and top-down modeling as complementary approaches	Does not assume energy is the only factor affecting technology choice	Simple, transparent and flexible. Capable of examining issue beyond technology choice	Powerful and consistent approach to analyze the costs of meeting a certain policy goal	Engineering-style description of the energy system	Identifying the least-cost combination for meeting a target
Weaknesses	Complex, opaque and the accuracy is heavily linked to the assumptions made and behavior correlations	Hard to apply for non-expert users and less useful in capacity building efforts	Does not take cost optimization	Generally assume perfect competition and energy is the only factor in technology choice	Does not take cost optimization	Not suit to examining options beyond power sector
Data Medium–high	requirements	Medium–high	Medium–high	Low–medium	Medium–high	Medium
Time horizon (scenario timeframe)	Medium-to long-term	Up to75 years. Annual results	No limit. Annual results	Max 50 years.	Medium-to long-term	50+ years
Technical support and cost	n.a.	Cost ≈$10,000	Email and web forum (free)	Cost ≈$500–2500 for one year	n.a.	n.a.
Number of users						
– Worldwide	Medium	Medium	Very high	High	Medium	High
– Thailand	Low	Low	High	Low	Low	Low

price-induced effects is the main weakness. According to the purpose of energy models applied in the review, all model used for scenario-based analyses of energy system development and assessing a number of interventions.

3.3. Some results of energy and emissions modeling studies in Thailand

Results of the energy demand and emissions in Thailand were compiled from previous studies in terms of final energy consumption and energy-related CO_2 emissions from different models and scenarios. These models applied for different base years and time horizons (2010, 2020, 2030, and 2050). Also, different modeling approaches have been employed in the models. It should be noted that different studies used different models and assumptions, and the relevant results may vary significantly. Furthermore, models were used to answer different types of questions. Table 4 summarizes major results of different studies on final energy demand while Table 5 presents relevant estimated CO_2 emissions from the models.

4. Backcasting and energy scenarios

4.1. Backcasting energy futures

Backcasting is an approach to explore the feasibility and impact of alternative futures with a focus on discovery rather than

Table 4
Comparison of final energy demand in Thailand under different models' scenarios (Mtoe).

Modeling exercise	Model	Base year	2010	2020	2030	2050
Winyuchakrit et al. [13]	Extended	2005				
BAU scenario	SnapShort	57.33	–	–	164.86	–
CM (Climate change mitigation measures) Scenario	Tool (ExSS)		–	–	128.97	–
Watcharejyothin and Shrestha [29]	MARKAL	2000				
BAU scenario		49.30	75.09	121.45	185.34	–
Pinthong and Wongsapai [28]	MAED (demand	2005				
BAU scenario	model) and MESSAGE (supply model)	61.35	–	–	164.22	–
Shrestha et al. [35]	AIM/Enduse model	200				
TA1 (Global market integration scenario)		49	82	–	114	201
TA2 (Dual track scenario)			75	–	197	450
TB1 (Sufficiency economy scenario)			77	–	173	337
TB2 (Local stewardship scenario)			69	–	165	326
TRF [44]	LEAP	2005	2011	2016	–	–
BAU scenario		62.47	85.74	112.09	–	–
EE (Energy efficiency) scenario			78.98	97.76	–	–
APEC [45]	–		86.5	139.7	189.9	–
Tanatvanit et al. [34][a]	LEAP	2000				
BAU scenario		39.72	60.54	88.32	–	–
EEI (Energy efficiency) scenario			60.54	88.21	–	–
PTI (Public transport) scenario			60.14	87.68	–	–
FEI (Fuel economy) scenario			60.30	87.82	–	–

[a] This study considers only three economic sectors, including residential, industrial and transport sectors. The commercial sector is excluded in the model.

Table 5
Estimation of CO_2 emissions from energy sector in Thailand ($MtCO_2$).

Modeling exercise	Model	Base year	2010	2020	2030	2050
Winyuchakrit et al. [13]	Extended	2005				
BAU Scenario	SnapShort	185.98	–	–	563.73	–
CM (Climate change mitigation measures) Scenario	Tool (ExSS)		–	–	403.64	–
Watcharejyothin and Shrestha [29]	MARKAL	2000				
BAU scenario		165	350	471	899	–
ADB [37]	DNE21+					
Reference	model		–	350	–	510
S550			–	275	–	420
S450			–	250	–	360
Shrestha and Pradhan [46]	MARKAL	2005				
Base case		223	300	475	750	2006
Shrestha et al. [35]	AIM/Enduse	2000				
TA1 (Global market integration scenario)	model	158	250	480	700	1312
TA2 (Dual track scenario)			220	400	580	1180
TB1 (Sufficiency economy scenario)			210	350	500	1150
TB2 (Local stewardship scenario)			200	280	380	647
TRF [44]	LEAP	2005	2011	2016		
BAU scenario		199	264	332		
EE (Energy efficiency) scenario			243	288		
APEC [45]	–	–	306.7	516.7	733.6	–
Tanatvanit et al. [34][a]	LEAP	2000				
BAU scenario		80	150	225	–	–
EEI (Energy efficiency) scenario			–	224.9	–	–
PTI (Public transport) scenario			–	222.9	–	–
FEI (Fuel economy) scenario			–	223.4	–	–
UNEP and World Bank [47]	–	–	490	810	–	–

[a] This study considers only three economic sectors, including residential, industrial and transport sectors. The commercial sector is excluded in the model.

justification. Backcasting aims to envisioning alternative futures, and to examining the transition paths by which these alternative futures may be realized. The generic backcasting steps are to specify goals and objectives in order to formulate a range of futures or scenarios, and to identify the changes that would need to be made to the current energy system to realize these futures or transition pathways [48]. A backcasting draws up a target image or an outcome to avoid and investigates for pathways to achieve it or to avoid it. The major concern in backcasting is how to attain desirable futures [49]. Backcasting studies can be characterized by specific methodological steps, which can differ between approaches [50,51].

The backcasting approach used in this paper is built on the early approaches developed by Robinson [49] and Höjer and Mattsson [52]. The backcasting/energy scenario approach is applied to explore a diverse set of options toward a low-carbon energy system in Thailand. A four-step method is applied to examine the transition pathways by which alternative futures can be realized. The first step is to define the problem, including establishment of target for what is to be attained. In the second step, current trends and forecasts are analyzed. The third step is to develop images of the future in which one or more alternative future images are developed. The final step is to analyze how the desirable futures can be realized. Since backcasting is an established approach and we did not aim to repeat the methodological development. Several authors have been applied backcasting in energy studies, for example [48,51,53–57]. The rational for using backcasting is that the outcomes from this study would use by government or relevant agencies as the input to policy development on low-carbon futures, and to support transition pathways.

In the analysis, the first step was to define a problem and analyze the target. The system boundary covers energy usage in all economic sectors i.e., household, commercial, industrial, transport, and agriculture sectors. For the emission target, it is not clearly specified by the Thai government both in terms of emission levels and target year. Therefore, in the review of modeling exercises, we chose to focus on 2030 target year. We target at CO_2 emissions from energy use only because it is the main source of CO_2 emissions in Thailand. In the second step, a survey was made of existing forecasts, trends and scenario studies dealing with future energy demand and CO_2 emissions covering the entire energy system in order to establish the possible targets. This allowed identifying potential measures for the transition paths. We did not make any calculations of our own, but based our conclusions on findings presented in [13,35,43,44,58]. In the third step, two scenarios were selected from existing energy scenarios that fit within the low-carbon scenario theme [13,41]. Similarly to the second step, no numerical modeling was recalculated due to data requirements and lack of modeling tools. These two scenarios were used for development of future images. This paper proposes an image of the future that Thailand's CO_2 emissions from the energy system in 2030 are 40% lower than 2005 levels. The two scenarios are discussed in the next section. The final step was to consider the changes from the current situation to realize future scenarios. This step is known as the establishment of transition pathways or migration pathways [59]. We collected potential measures for achieving future image and developed an estimated roadmap for Thailand's low-carbon energy system. According to the analysis processes, this study presents an exploration of the energy sector's low-carbon options for reductions in CO_2 emissions while maintaining economic growth. This can bring Thailand to take the leading role in the region. The study can also support the negotiating position in the United Nations Framework Convention on Climate Change negotiations. It can contribute to facilitate the preparation and implementation of low-carbon development strategies and Nationally Appropriate Mitigation Actions (NAMAs).

4.2. Energy scenarios and low-carbon futures for Thailand

Energy scenarios are widely used to outline possible pathways for low-carbon futures. Energy scenario studies are distinguished by either quantitative model or on qualitative information. Scenario-based modeling helps to understand where a country or a particular sector currently stands and the direction in which it is moving with respect to energy demand and CO_2 emissions. It helps to identify drivers, measures and resources required for reductions of energy demand and associated emissions.

Energy scenarios in this paper are based on a critical review of existing scenario exercises for meeting the 2030 target year. Qualitative scenario is not included in the review. In the review, we selected two baseline scenarios (scenario A and B) from the recent studies [13,41]. The rational for selecting these two studies is that they analyze on the same time horizon (until the year 2030). They also lie on studies to address the energy system development and environmental implications.

Scenario A developed by Winyuchakrit et al. [13] applies a macro-economic model to estimate future socio-economic indicators such as population, number of households, GDP, floor space, and passenger transport demand. This scenario makes considerable environmental gains together with economic growth. It provides opportunity for Thailand to achieve low-carbon energy system related to energy technology, renewable energy utilization and energy efficiency improvements. The findings show that the share of primary industry, including agriculture and mining sectors would decrease from 6.0% in 2005 to 4.1% in 2030. The share of manufacturing industry would decrease from 61.1% in 2005 to 55.5% in 2030. However, the share of service sector would increase from 33.0% in 2005 to 40.4% in 2030. The number of households is expected to increase from 19 million to 36.3 million in 2005 and 2030. Total floor space of commercial buildings would increase from 88 million square meters (2005) to 394 million square meters (2030). Passenger transport demand would increase from 191,520 million passenger-kilometers in 2005 to 216,088 million passenger-kilometers in 2030. Freight transport demand would increase from 188,524 million ton-kilometers to 589,859 million ton-kilometers in 2005 and 2030, respectively. The final energy demand in Thailand is projected to increase from 57,327 ktoe in 2005 to 164,863 ktoe in 2030. Total CO_2 emissions are estimated to increase from 186 $MtCO_2$ to 564 $MtCO_2$ in 2005 and 2030, respectively. The transition path under this scenario will require comprehensive policy planning and actions. Usually, it takes time to implement low-carbon measures and changes current energy infrastructure. Therefore, it is important to consider a low-carbon development in the goal of national plan.

The scenario B developed by Wangjiraniran et al. [41] assumes the future prospect under current energy policy without change of economic structure. National Renewable Development Plan (REDP) and Power Development Plan 2010 (PDP 2010) are taken into account. Accordingly, the long-term GDP growth is expected to be 4% annually. This scenario assumes that industrial and commercial sector would increase their contribution to the Thailand's economy, while activities in the agricultural sector would decrease. The scenario focuses on the economic structure toward an innovative driven and service-based economy. It is found that the shares of value-added from industrial and commercial sectors are expected to be 39.4% and 38.8% in 2030. Transport, agriculture and others are expected to contribute 10.2%, 7.5% and 4.1%, respectively. Other key assumptions include number of population, sectoral energy intensity, switching from road to rail transportation, renewable energy market, and fuel options for power generation. The utilization of renewable energy target is based on REDP (more detail see, DEDE [60]) while options for energy mix in power generation is based on PDP 2010 (more

detail see, EGAT [61]). In this scenario, transport and industrial sectors are still the major shares of final energy demand in Thailand in 2030. Power generation would contribute the largest share of CO_2 emissions, approximately 115 $MtCO_2$. Other two major emission sectors are transport and industry that would emit approximately 100 $MtCO_2$ and 70 $MtCO_2$, respectively. The transition path under this scenario will require economic restructuring. The structural shift in economic activities will affect total energy demand and consequently energy-related CO_2 emissions.

4.3. Roadmap for Thailand's low-carbon energy system

Technology options, energy system transitions and CO_2 emission pathways are explored based on the backcasting/energy scenario approach. Usually, low-carbon energy systems are concerned with energy efficiency and clean energy mix. The main features of achieving low-carbon energy systems are energy technology innovation and institutional innovation [62]. These can be achieved through a combination of strategies, including managing the growth in energy service demand, increasing investments in energy efficiency and low-carbon energy supply technologies, and revision of institutional arrangements.

In this paper, we develop a roadmap of low-carbon options and estimated their schedule toward a given target year (2030). We employ the options shown in previous studies in Thailand related to energy efficiency improvement, renewable energy utilization, and climate change mitigation. A list of potential low-carbon options is compiled from Ministry of Energy [63] and other references, including [13,33,35,44,58]. A roadmap helps to support decision-making to achieve economic growth while managing a low-carbon energy system and receiving co-benefits in energy efficiency improvement, renewable energy and environmental protection. Fig. 3 shows estimated roadmap that consists of the implementation of options. The gray lines in the figure indicate that the option concerned continues after having fully penetrated. Penetration means diffusion or proceeding of the options. Although the options in the figure are those indicated in previous studies, some of the parameters, such as implementation period,

Fig. 3. Estimated roadmap of Thailand's low-carbon energy system.

accelerating ratio and rate of penetrations, are revised in this study. Thus, the roadmap developed in this paper is proposed as alternative for achieving a low-carbon energy system.

International climate considerations are not the only reason why developing countries such Thailand are exploring low-carbon development pathways. Throughout Asia and across the rest of the world are designing and implementing low emission development strategies to harmonize the planning, analysis and policy-making that together make possible low-carbon development. From a climate change mitigation perspective, Thai Government is keenly aware of the opportunities associated with green growth and the risks of being locked into high carbon infrastructure. In an effort to get onto a sustainable development path, the National Economic and Social Development Board (NESDB) 11th Five-Year Plan (2011–2015) has put green growth and LCS as one of the central themes. Decoupling economic growth from carbon emissions is increasingly a policy goal for national benefit [64]. The roadmap developed in this paper identifies technologies and actions to reduce CO_2 emissions and provides technical inputs to undertake a low-carbon energy system. There are significant opportunities to benefit from the implementing low-carbon measures. Thailand can take advantage of the opportunities from developing low-carbon energy system and gaining competitive advantages in some areas such as bioenergy and energy efficiency improvement. A low-carbon development could serve to transform resource intensive growth to a more efficient pathway.

Policy instruments that help frame effective policies are crucial in implementing the roadmap. Short-term policy needs to increase the implementation of renewable energy, energy efficiency improvement and other green development. Long-term policy should address fundamental changes toward LCS. The roadmap can support a range of other policy goals, including economic competitiveness, energy security, the development of new industries and jobs, and local environmental protection. The roadmap can be implemented under the current directions of energy policies, including the REDP (2009–2022), PDP 2010 and the 20-Year Energy Efficiency Plan (2010–2030) [60,61,63,64]. Some measures could be implemented through the clean development mechanism or other international carbon finance mechanisms.

The obstacles of implementing measures in the roadmap still exist. A number of barriers are ranging from inexperience and the lack of information to incompatibility with industry norms and other standards. Data collection and data sharing across different agencies also pose a challenge. Many measures in the roadmap face a variety of market and non-market barriers. Policies to promote low-carbon measures still exist, but new policies or changes in existing policies are needed to accelerate the implementation. The barriers in the industrial and building sectors are limited awareness of energy efficiency and risks of new technologies and actions. The transport sector faces political, financial and social barriers. Additional works are needed to assess the barriers that inhibit low-carbon interventions from being implemented and how such barriers can be overcome.

In Thailand, the goal of setting a LCS is handled by national council with implementation delegated to energy, environment and other agencies. Achieving a low-carbon energy system requires the strengthening institutional arrangements. Based - on existing institutional arrangements in Thailand and international experiences, a national champion with high-level authority to lead effective institutional coordination is critical to lead the effort. Thailand has established high-level cross-ministerial committee on climate change and the Climate Change Master Plan 2012–2050, which is a framework of integrated policies and action plans relating climate change [65]. This committee can effectively involve and coordinate with key sector ministries.

5. Conclusions

In this paper, we present a comparative study of existing energy scenario studies and energy systems modeling with an objective of evaluating energy models that have been applied for Thailand. We have reviewed a number of models covering energy systems and organized literature on the low-carbon energy scenarios into three categories, including trend-based studies, technical feasibility studies and modeling studies. The energy scenarios reviewed in this paper have made important steps toward imagining and quantifying such possible futures. To achieve a low-carbon energy system, it is certainly that Thailand must involve technical, social and political arrangements that help to frame effective policies for low-carbon development.

Thailand's transition toward a low-carbon energy system should not only follow the general rules of socio-economic development and international agreement on climate protection, but should consider the basic of national conditions and interests. It has been recognized that it is crucial for all nations to undertake GHG mitigation. All mitigation actions in Thailand are taken voluntary with the aim of being part of the global action in reducing GHG emissions. This paper proposes that Thailand should adopt measures for low-carbon energy system development under a comprehensive framework in the next 20 years. By 2030, Thailand's energy-related emission target would be set at 30–40% reductions below 2005 levels. In our review and analyses, technically it is possible to achieve the 2030 target if all identified potentials in the estimated roadmap are fully realized. Thus, Thailand's energy-related CO_2 emissions could be expected to peak in 2030 and then stabilize and start to decline afterwards. The recommendation for Thailand's reduction goal can provide the direction for plausible pathway of low-carbon energy system. Information gained from this study can use for supporting the climate change negotiations in the future, especially if developing countries will be forced to reduce their emissions. In this case, the suggested roadmap can provide a comprehensive list of policy options and practical implementing strategies to pursue low-carbon energy system based on national priorities and circumstances.

Moreover, the transition governance for low-carbon futures is another important issue to be considered in the pathways as well. While energy scenarios contribute to envisage possible low-carbon energy systems it is equally important to address the societal transitions implied by these futures, and investigate how these can be governed, implemented and achieved. A low-carbon energy system is not only improve environmental sustainability but it will bring co-benefits, including enhanced energy security, less air pollution, more livable, and greater competitiveness from higher productivity.

Acknowledgments

Authors wish to acknowledge the Department of Industrial Engineering, King Mongkut's University of Technology North Bangkok, Thailand for collaborative research. Some portion of this paper was conducted under the Research Policy in the Context of Sustainable Development and Low Carbon Economy Project. Authors would like to thank for the financial support and the guidance of the project's steering committee and the consultation workshop. Finally, the Authors would like to thanks for reviewers' comments and suggestions on this paper.

References

[1] Abdelaziz EA, Saidur R, Mekhilef S. A review on energy saving strategies in industrial sector. Renewable and Sustainable Energy Reviews 2011;15(1): 150–168.

[2] IEA (International Energy Agency). World Energy Outlook 2010, International Energy Agency Publication; 2010.
[3] U.S. Energy Information Administration. International Energy Statistic Database: World energy-related carbon dioxide emissions: 1980–2010, Available online at: 〈http://www.eia.gov/ies〉 [Accessed 21.06.12].
[4] Nakata T, Silva D, Rodionov M. Application of energy system models for designing a low-carbon society. Progress in Energy and Combustion Science 2011;37(4):462–502.
[5] Verbruggen A. Beyond Kyoto, Plan B: a climate policy master plan based on transparent metrics. Ecological Economics 2009;68:2930–7.
[6] Goldemberg J, Prado LT. The decarbonization of the world's energy matrix. Energy Policy 2010;38(7):3274–6.
[7] Kaya Y. Impacts of carbon dioxide emission control on GDP growth: Interpretation of proposed scenarios. Paper presented at IPCC Energy and Industry Subgroup, Response Strategies Working Group: Paris, France; 1990.
[8] Grübler A. Transitions in energy use. In: Cleveland CJ, editor. Encyclopedia of Energy. San Diego: Elsevier; 2004. p. 163–77.
[9] Skea J, Nishioka S. Policies and practices for a low-carbon society. Climate Policy 2008;8:S5–16.
[10] Shimada K, Tanaka Y, Gomi K, Matsuoka Y. Developing a long-term local society design methodology towards a low-carbon economy: an application to Shiga Prefecture in Japan. Energy Policy 2007;35:4688–703.
[11] Berkhout F, Marcotullio P, Hanaoka T. Understanding energy transitions. Sustainability Science 2012;7:109–11.
[12] DEDE (Department of Alternative Energy Development and Efficiency). Thailand Energy Statistic 2011. Ministry of Energy: Bangkok; 2011.
[13] Winyuchakrit P, Limmeechokchai B, Matsuoka Y, Gomi K, Kainuma M, Fujino J, Suda M. Thailand's low-carbon scenario 2030: analyses of demand side CO_2 mitigation options. Energy for Sustainable Development 2011;15 (4):460–6.
[14] NESDB (National Economic and Social Development Board) and World Bank. Thailand: Clean Energy for Green Low-Carbon Growth: Bangkok, Thailand; 2011.
[15] Clarke L, Edmonds J, Krey V, Richels R, Rose S, Tavoni M. International climate policy architectures: overview of the EMF 22 international scenarios. Energy Economics 2009;31(2):S64–81.
[16] Edenhofer, et al. The economics of low stabilization: model comparison of mitigation strategies and costs. The Energy Journal 2010;31(1):11–48.
[17] IEA (International Energy Agency), Energy Technology Perspective 2010: Scenario and Strategies to 2050. Organization for Economic Co-operation and Development (OECD): Paris, France; 2010.
[18] GEA: Global Energy Assessment—Toward a Sustainable Future, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis: Laxenburg, Austria; 2012.
[19] McCollum D, Yang C, Yeh S, Ogden J. Deep greenhouse gas reduction scenarios for California—strategic implications from the CA-TIMES energy-economic systems model. Energy Strategy Reviews 2012;1:19–32.
[20] Hughes N, Strachan N. Methodological review of UK and international low carbon scenarios. Energy Policy 2010;38(10):6056–65.
[21] NIDA (National Institute of Development Administration). Thailand Long-Term Load Forecasts. Report submitted to the Energy Policy and Planning Office: Bangkok, Thailand; 2006.
[22] Charusiri W, Ubolwat J. The Energy Forecasting Model for Provincial Energy Planning. In: Proceedings of the 3rd Conference on Energy Network of Thailand (E-NETT 2007): Bangkok, Thailand; 23–25 May 2007.
[23] Limanond T, Jomnonkwao S, Srikaew A. Projection of future transport energy demand of Thailand. Energy Policy 2011;39(5):2754–63.
[24] Limmeechokchai B, Chaosuangaroen P. Assessment of Energy Saving Potential in the Thai Residential Sector: Long-range Energy Alternatives Planning Approach. In: Proceedings of the 2nd Joint International Conference on Sustainable Energy and Environment (SEE 2006): Bangkok, Thailand; 21–23 November 2006.
[25] Limmeechokchai B, Suksuntornsiri P. Assessment of cleaner electricity generation technologies for net CO_2 mitigation in Thailand. Renewable and Sustainable Energy Reviews 2007;11:15–330.
[26] Shrestha RM, Pradhan S, Liyanage MH. Effects of carbon tax on greenhouse gas mitigation in Thailand. Climate Policy 2008;8:140–55.
[27] Pongthanaisawan J, Sorapipatana C. Technology alternatives for energy demands reduction and greenhouse gases emissions mitigation in Thailand's road transport sector. In: Proceedings of the 4th Conference on Energy Network of Thailand (E-NETT 2008): Nakhon Phatom, Thailand; 4 May 2008.
[28] Pinthong T, Wongsapai W. Evaluation of energy demand and supply under electricity generation scenarios of Thailand. In: Proceedings of the World Renewable Energy Congress 2009—Asia—the 3rd International Conference on Sustainable Energy and Environment (SEE 2009): Bangkok, Thailand; 18–23 May 2009.
[29] Watcharejyothin M, Shrestha RM. Regional energy resource development and energy security under CO_2 emission constraint in the greater Mekong subregion countries (GMS). Energy Policy 2009;37(11):4428–41.
[30] Eakpaopan W, Wongsapai W, Vorayos N, Mai C. Forecasting of renewable energy demand and supply of Thailand. Engineering Journal Chiang Mai University 2009;16(3):49–54.
[31] Chaivongvilan S, Sharma D. Long-term impacts of alternative energy-environmental scenarios for Thailand.Energy Planning and Policy Program. Sydney, Australia: University of Technology; 2009.
[32] Phdungsilp A, Wuttipornpun T. Energy and carbon modeling with multi-criteria decision-making towards sustainable industrial sector development in Thailand. Low Carbon Economy 2011;2:165–72.
[33] Chollacoop N, Saisirirat P, Fukuda T, Fukuda A, Metal N. Scenario analyses of road transport energy demand: a case study of ethanol as a diesel substitute in Thailand. Energies 2011;4:108–25.
[34] Tanatvanit S, Limmeechokchai B. Sustainable energy development strategies: implications of energy demand management and renewable energy in Thailand. Renewable and Sustainable Energy Reviews 2003;7: 367–395.
[35] Shrestha RM, Malla S, Liyanage MH. Scenario-based analyses of energy system development and its environmental implications in Thailand. Energy Policy 2007;35(6):3179–93.
[36] Mulugetta Y, Mantajit N, Jackson T. Power sector scenarios for Thailand: an exploratory analysis 2002–2022. Energy Policy 2007;35: 3256–3269.
[37] ADB (Asian Development Bank). The Economics of Climate Change in Southeast Asia: Regional Review. Available online at 〈www.adb.org〉; 2009 [Accessed 26.06.10].
[38] Phdungsilp A. Integrated energy and carbon modeling with a decision support system: policy scenarios for low-carbon city development in Bangkok. Energy Policy 2010;38(9):4808–17.
[39] Suwanapal P. Spatial Energy System Modelling under Uncertainty with application to Thailand. Ph.D. Thesis. Department of Chemical Engineering and Chemical Technology, Imperial College London: UK; 2010.
[40] Wangjiraniran W. The Outlook of Long-term Energy-related GHG in Thailand. In: Proceedings of the 6th Conference on Energy Network of Thailand (E-NETT 2010): Bangkok, Thailand; 5–7 May 2010.
[41] Wangjiraniran W, Vivanpatarakij S, Nidhiritdhikrai R. Impact of economic restructuring on the energy system in Thailand. Energy Procedia 2011;9:25–34.
[42] UNFCCC (United Nations Framework Convention on Climate Change). Training Handbook on Mitigation Assessment for Non-Annex I Parties. Available online at 〈http://unfccc.int/resource/cd_roms/na1/mitigation/index.htm〉; 2006 [Accessed 03.06.10].
[43] Phdungsilp A. Review of the Energy Models for Low-Carbon Economy Planning. Research Report, Policy Research on Thailand's Climate Change in the Context of Sustainable Development and Low Carbon Economy, Southeast Asia START Regional Center: Bangkok, Thailand; 2010.
[44] TRF (Thailand Research Fund). Research Programme on Policy Research for Promoting the Development and Utilisation of Renewable Energy and the Improvement of Energy Efficiency in Thailand. Final Report: Bangkok, Thailand; 2008.
[45] APEC (Asia-Pacific Economic Cooperation). APEC Energy and Supply Outlook 2006. Available online at: 〈http://www.ieej.or.jp/aperc/2006pdf/Outlook2006/Whole_Report.pdf〉 [Accessed 15.09.09].
[46] Shrestha RM, Pradhan S. Analyzing Co-benefits of Greenhouse Gas Mitigation Targets and Measures in Thailand. In: Better Air Quality (BAQ) 2008 Workshop: Bangkok, Thailand; 12–14 November 2008.
[47] UNEP (United Nations Environmental Programme) and World Bank. Climate Change Mitigation in Asia and Financing Mechanisms: Country Presentation. In: Proceedings of a Regional Conference: Goa, India; 4–6 May 1998.
[48] Giurco D, Cohen B, Langham E, Warnken M. Backcasting energy futures using industrial ecology. Technological Forecasting and Social Change 2011;78(5): 797–818.
[49] Robinson JB. Futures under glass: a recipe for people who hate to predict. Futures 1990;22(8):820–42.
[50] Quist J. Backcasting for a sustainable future: the impact after 10 years. PhD Thesis, Faculty of Technology, Policy and Management, Delft University of Technology, Delft: the Netherlands; 2007.
[51] Svenfelt A, Engström R, Svane Ö. Decreasing energy use in buildings by 50% by 2050—a backcasting study using stakeholder groups. Technological Forecasting and Social Change 2011;78(5):785–96.
[52] Höjer M, Mattsson LG. Determinism and backcasting in future studies. Futures 2000;32:613–34.
[53] Robinson J. Energy backcasting: a proposed method of policy analysis. Energy Policy 1982;10:337–44.
[54] Mulder H, Biesiot W. Transition to a Sustainable Society—a Backcasting Approach to Modelling Energy and Ecology. Cheltenham, UK: Edward Elgar; 1998.
[55] Anderson K. Reconciling the electricity industry with sustainable development: backcasting—a strategic alternative. Futures 2001;33:607–23.
[56] Phdungsilp A. Futures studies' backcasting method used for strategic sustainable city planning. Futures 2011;43(7):707–14.
[57] Ashina S, Fujino J, Masui T, Ehara T, Hibino G. A roadmap towards a low-carbon society in Japan using backcasting methodology: Feasible pathways for achieving an 80% reduction in CO_2 emissions by 2050. Energy Policy 2012;41:584–98.
[58] Sawangphol N, Pharino C. Status and outlook for Thailand's low carbon electricity development. Renewable and Sustainable Energy Reviews 2011;15(1):564–73.
[59] Dortmans PJ. Forecasting, backcasting, migration landscapes and strategic planning maps. Futures 2005;37:273–85.
[60] DEDE (Department of Alternative Energy Development and Efficiency). Renewable Energy Development Plan 2009–2022 (REDP). Ministry of Energy: Bangkok, Thailand; 2009.

[61] EGAT (Electricity Generating Authority of Thailand), 2010. Power Development Plan 2010–2030 (PDP 2010). Electricity Generating Authority of Thailand; 2010.
[62] Liu C, Feng Y. Low-carbon economy: theoretical study and development path choice in China. Energy Procedia 2011;5:487–93.
[63] Ministry of Energy. Thailand's renewable energy and its energy future: opportunities and challenges. Ministry of Energy: Bangkok; 2009.
[64] UNESCAP (United Nations Economic and Social Commission for Asia and the Pacific). Low Carbon Green Growth Roadmap for Asia and the Pacific. Available online at ⟨www.unescap.org/esd/environment/lcgg;%202012⟩ [Accessed 25.04.12].
[65] Chamornmarn P. Potential of Thailand's NAMAs and MRV. Presented at the 2012 International Forum for Sustainable Asia and Pacific Expert Meeting: Yokohama, Japan; 25 July 2012.